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A Combined Energy and Geoengineering Optimization Model (CEAGOM) for climate and energy policy analysis

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HIGHLIGHTS

- An energy optimization model incorporating geoengineering is described.
- The model employs commercial software and runs quickly.
- Model results compare well with a similar US government analysis.
- The model can be of use to policy-makers, researchers, and students.

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ABSTRACT

Addressing greenhouse gas emissions and the associated global temperature rise will be one of the key issues of the 21st century. The supply and use of energy is the single largest contributor to anthropogenic greenhouse gas emissions through the burning of fossil fuels. Given the role fossil fuel use plays in the global economy, curtailing their use in order to mitigate climate change will be very difficult. This has led to proposals to deploy various types of geoengineering as a means of mitigating the global temperature increase. Current integrated assessment models (IAMs) do not readily incorporate geoengineering options. They are also complex to set up and run. This has led the authors to develop the Combined Energy and Geoengineering Optimization Model (CEAGOM)©. CEAGOM provides an easy to use software platform that explicitly includes geoengineering as potential options as part of the optimization of the energy resource mix for meeting a specified energy demand while still meeting specified climate targets. This paper describes the CEAGOM model and shows that its results compare quite favorably with those from a more complex IAM.

1. Introduction

One of the greatest challenges that humanity will face over the coming decades is global climate change. The concentration of carbon dioxide in the atmosphere from greenhouse gas emissions (GHG) is well on track to double from the level present prior to the Industrial Revolution by the end of the 21st century with associated significant changes in global climate [1]. The energy sector is the largest contributor of global GHG emissions through the use of fossil fuels [2]. The steps that would be required to reduce greenhouse gas emissions through reductions in the use of fossil fuels would involve huge economic and social impacts [3]. This imposes significant inertia and resistance on the part of both governments and the general public to take any substantial action in the near term to cut greenhouse gas emissions as can be clearly seen in the reaction to the Paris Accord [4,5].

This serious quandary has led many researchers to suggest that various kinds of artificial measures could be taken that would counteract the heating effects (or as they are more properly called the radiative forcing) of increased greenhouse gas concentrations while still allowing the burning of fossil fuels. These proposals range from the injection of aerosol particles into the stratosphere (to mimic the effects of volcanic eruptions in blocking the sun) to setting up a vast artificial sun shade in space between the earth and the sun [6–13]. Another

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approach that has been proposed is to enhance natural processes in order to remove additional CO_2 from the atmosphere, such as by fertilizing the ocean with iron [14]. These various proposals are collectively known as geoengineering.

The concept of using geoengineering approaches to mitigate climate change is highly controversial and potentially risky [15–19]. Some authors have suggested that geoengineering technology be explored for emergency preparedness in the event it becomes clear that the earth's climate is heading for a potentially catastrophic outcome [20–23]. It has even been suggested that the positive aspects of geoengineering may be attractive enough for some countries that they would be willing to undertake some geoengineering efforts unilaterally [24]. For these reasons, the National Academy of Sciences has recommended that careful research into geoengineering and its potential impacts be undertaken [25,26].

Given the importance of energy supply to global economic well-being and its significant role in climate change, having a means of analyzing what would be an optimal mix of energy resources to meet global energy demand while meeting desired climate limits is crucial. This means that the models and their outputs need to be easily accessible by a wide range of users, including researchers, policy-makers, and students. Furthermore, given the role geoengineering may play in the future, having models that readily include geoengineering options as part of the analysis will be important. A number of very good integrated assessment models (IAMs) exist (e.g. TIMES, GCAM, and NEMS). A drawback of these IAMs; however, is that they are complex pieces of software that require very extensive input data sets and often considerable time to run [27–29]. Furthermore, they do not readily incorporate a range of geoengineering options. This need for an accurate, easy to use energy resource and climate limits optimization model that can be accessed by a variety of users and which also incorporates the concept of geoengineering led the authors to develop the Combined Energy and Geoengineering Optimization Model (CEAGOM)©.

2. Model description

2.1. Overview

CEAGOM contains components that implement widely-accepted theoretical models, as well as additions and modifications developed by the authors, related to employment of available energy resources and/or geoengineering alternatives to achieve projected global or regional energy needs over any time horizon specified by the user. Importantly, CEAGOM incorporates an optimization engine that allows the user to input posited constraints on either emissions, global average temperature, or radiative forcing, based on which it then derives an optimal mix of available energy resources and geoengineering alternatives to achieve the projected energy needs posited by the user. In addition, CEAGOM allows the policy-maker to inquire how the calculated optimal mix changes as key model parameters (such as cost) are varied. Nearly all of the engineering, climate, and economic parameters used in the model are user-defined. Refer to Appendix A for the definitions of the variables used in the remainder of this paper.

CEAGOM comprises four primary components: an energy model, a climate model, an economics model, and an optimization engine. CEAGOM starts with a user supplied energy forecast for the time period of interest. This forecast stipulates the expected amount of energy to be needed in the time period of interest. The energy forecast is specified in units of exajoules (1 EJ = 10^{18} J). This is consistent with how the Intergovernmental Panel on Climate Change (IPCC) specifies energy forecasts in their documentation. All time steps in CEAGOM are considered to be annual increments. A portfolio of energy resource options for meeting this total energy demand is chosen by the optimization engine from a list that has been programmed into the model. In addition, the optimization engine adds a mix of geoengineering options, if necessary to meet specified emissions or radiative forcing constraints, from another list that has been preprogrammed into the model. The model also respects resource specific constraints, such as the amount of resource available, resource lifetime, and maximum amounts that can be added or removed at each time step. The objective of the model is to determine the least cost portfolio of energy resources and geoengineering needed to meet the given energy demand for each year of the simulation while respecting the specified climate and resource constraints. This combination of energy resources and geoengineering constitutes a "policy" very much along the lines of those used in optimal control problems [30].

CEAGOM provides several outputs. The first is an optimized set of energy resource and geoengineering amounts for each year of the simulation. It also outputs the corresponding total cost (as both a nominal value and a net present value), total annual or cumulative emissions (depending on the specific analysis run), equivalent CO_2 concentration, radiative forcing, and global average temperature change for each year of the simulation.

The CEAGOM code itself is written entirely in MATLAB©. CEAGOM also uses standard Excel© files for its output data and several of its key input data. All other input data is contained in the MATLAB code and can be easily modified by the user. MATLAB and Excel are widely-used and available software platforms. Hence, this makes CEAGOM readily accessible to a wide range of users, including researchers, policy-makers, and students.

2.2. Energy model

CEAGOM uses an energy demand forecast that is comprised of four components: a forecast of the total demand, the subset of the energy demand that is associated with liquid fuel needed for transportation, the subset of energy demand that must be met with electricity, and the subset of demand associated with heating needs (predominately industrial) that has to be met with combustible fuels. The energy demands are specified in terms of what the IPCC terms as "final energy". The IPCC defines three levels of energy. Primary energy is the energy stored in the unprocessed energy resource (e.g. crude oil, uranium, or coal). IPCC then uses a method called the direct equivalent method to determine what is called secondary energy. For combustible fuels, secondary energy under the direct equivalent method is defined as the energy potential of the fuel after it has been refined or cleaned (as in the case of oil and natural gas, respectively), but prior to actually burning the fuel. For non-combustible fuels such as hydro power or wind, one unit of secondary energy is considered the same as one unit of primary energy. Secondary energy is considered final energy when it is finally delivered to the end-user for the purpose of providing useful work, such as electricity delivered at the wall socket [31].

One added feature of CEAGOM is the ability for the user to specify a certain amount of energy reserves to be carried as part of the simulation. This reserve amount is specified as a percentage of the actual energy demand and is considered a separate quantity from the actual energy demand. This energy reserves feature was included since some amount of reserves are carried in actual practice to cover in the event of unforeseen events, such as political strife, natural disasters, unexpected energy demand, or loss of other energy resources. An example of this type of reserve would be the United States Strategic Petroleum Reserve [32]. The only resources used in CEAGOM to meet any specified energy reserve requirements are oil, natural gas, coal, biofuel, biomass, hydropower, and geothermal. This is because these resources can be stored for extended periods of time (either in reservoirs, barrels, or piles on the ground) and then deployed if needed. This reserves feature is not intended to simulate short-term energy storage capabilities that would be used to store excess production from renewable energy resources.

The current implementation of CEAGOM incorporates the following energy resources: biofuel for combustion, biofuel for transportation, biomass, coal for combustion, coal for electricity, coal-to-liquids, energy efficiency, geothermal, hydropower, natural gas for combustion,

natural gas for electricity, oil for combustion, oil for transportation, nuclear, solar-PV, solar-thermal, and wind. The resources that can be used for reserves are oil, natural gas, coal, biomass, biofuel, hydroelectric, and geothermal.

The energy produced by any specific resource in the model is given by:

$$Q_j(t) = q_j(t)k_j\eta_j \tag{1}$$

Eq. (1) is a very standard energy conversion equation. The parameter $q_j(t)$ represents the amount of a given resource deployed at time t. It is specified in the commonly used units for that particular resource (e.g. billion barrels of oil, metric tons of coal, Terrawatts of wind and hydro power). The parameter k_j represents the amount of energy (in EJ) contained in each unit of the resource, such as the energy in a billion barrels of oil or the energy produced by 1 TW of wind turbines if they ran continuously for 1 year. The parameter η_j represents the "mine-to-final use" efficiency in producing and converting the resource into final energy for resources like oil, coal, and natural gas that have to be burned in order to produce useful energy. In the case of electricity based resources such as wind, hydro, and solar, η_j is the capacity factor of the resource since these resources do not operate continuously for an entire year. In this way, all of the various types of resources in the CEAGOM model are converted into a consistent energy value.

The total energy produced at each time step is simply the sum of the individual $Q_i(t)$'s. In addition, the model insures that the resources deployed that can meet electricity, combustion, and liquid demands produce at least enough energy to meet the respective subset of energy demand. For example, the amount of liquid energy resources deployed at each time step are at least equal to the liquid transportation fuel demand:

$$Q_{liquid}(t) = Q_{oil}(t) + Q_{biofuel}(t) + Q_{coal-l}(t) + Q_{efficiency-t}(t) \geqslant f_{liquid}(t) \tag{2}$$

Similarly, CEAGOM contains explicit constraints that require the amount of electricity generated at each time step and the amount of combustible fuels deployed at each time step to be at least equal to the electricity and combustion fuel demands, respectively:

$$\begin{aligned} Q_{electric}(t) = {} & Q_{coal-e}(t) + Q_{gas-e}(t) + Q_{nuclear}(t) + Q_{hydro}(t) + Q_{wind}(t) \\ & + Q_{solar-PV}(t) + Q_{solar-thermal}(t) + Q_{geothermal}(t) + Q_{biomass}(t) \\ & + Q_{efficiency-e}(t) \geqslant f_{electric}(t) \end{aligned} \tag{3}$$

$$\begin{aligned} Q_{combust}(t) = {} & Q_{oil-c}(t) + Q_{gas-c}(t) + Q_{coal-c}(t) + Q_{biofuel-c}(t) \\ & + Q_{efficiency-c}(t) \geqslant f_{combust}(t) \end{aligned} \tag{4}$$

It should be noted that the sum of the liquid, electric, and combustion energy demand subsets is less than the total energy demand. This is because there is a significant portion of the total energy demand that can be met with any type of energy resource. For instance, residential heating can be met with either a gas furnace or an electric heat pump.

Resources which can be used to meet two different types of energy demand are treated as two separate resources in the tool. This is because of different energy conversion efficiencies to meet the different energy demand types. For example, natural gas can be used for direct heating as part of the combustion energy demand or can be used to generate electricity. However, directly burning gas in a furnace for heating applications has a much higher efficiency (roughly 90%) than using it to meet an electric power demand (which only has an efficiency of around 45%). Hence, gas used to meet energy demand via direct combustion is a different energy resource in CEAGOM than gas used to meet energy demand in the form of electricity.

CEAGOM uses a simple, but effective approach to model energy efficiency as a resource. Energy efficiency is applied towards the electricity, transportation and combustion energy demand subsets; however, CEAGOM does not treat energy efficiency as multiple resources. Rather, a portion of the overall energy efficiency deployed is allocated to the electricity, combustion, and transportation demands as follows:

$$Q_{efficiency-e}(t) = \frac{f_{electric}(t)}{f_{total}(t)} \tag{5}$$

$$Q_{efficiency-c}(t) = \frac{f_{combust}(t)}{f_{total}(t)} \tag{6}$$

$$Q_{efficiency-t}(t) = \frac{f_{transport}(t)}{f_{total}(t)} \tag{7}$$

The total amount of energy efficiency available was based on the work of Krewitt et al. [33]. CEAGOM computes the energy efficiency limit as a percentage of the final energy demand:

$$q_{efficiency}(t) \leqslant L_{efficiency} \times f_{total}(t) \tag{8}$$

2.3. Climate model

In addition to these standard constraints related to resource amounts and required energy demands, CEAGOM employs climate-related constraints in its optimization. CEAGOM allows the user to pick one of four climate-related constraints to use in a given simulation: equivalent CO_2 concentration, total cumulative emissions, total annual emissions, and global average temperature rise. These parameters are all computed by the climate model. In addition, the climate model is also where the impacts of any geoengineering are computed. CEAGOM incorporates four types of geoengineering: atmospheric sulfur injection, sea spray injection, iron seeding of the oceans, and tree planting.

CEAGOM accounts for both CO_2 and CH_4 emissions associated with energy production. All energy resources, including renewables such as hydro, wind, and solar, are assumed to have some amount of CO_2 emissions. In the case of renewables, these CO_2 emissions arise during the fabrication of the resource. Their emissions are assumed to drop to zero once they are in operation. Methane emissions are associated with the use of coal, oil, and natural gas.

In addition to emissions associated with the production and use of energy resources, there are considerable emissions of CH_4 related to non-energy related human activities. Furthermore, N_2O is another powerful greenhouse gas with significant emissions largely related to agricultural activities [34]. As a result, CEAGOM also incorporates emissions of non-energy related CH_4 and N_2O as exogenous inputs to its climate model and computes their contribution to overall radiative forcing. The impact of these non-energy GHG emissions is particularly important when attempting to analyze the amount of geoengineering that may be required.

Carbon dioxide emissions at each time step are determined based on the specific energy resources deployed. In addition, since tree planting, iron seeding, and the production of biomass and biofuel all sequester CO_2, the overall CO_2 emissions at each time step are reduced by their deployment. Methane emissions at each time step are the sum of the emissions associated with the deployed energy resources plus the exogenous non-energy emissions input to the model. These annual GHG emissions constitute an emissions pulse at each time step.

Each of the three greenhouse gases in CEAGOM have a lifetime in the atmosphere. Therefore, each emissions pulse decays over time. For CO_2, this decay is given by the following equation from Table 2.14 of [35]:

$$CO_2\ PulseDecay = S_{co2}(w) \times (a_0 + \sum_{i=1}^{3} a_i e^{-(t-w)/tau_i}), \quad \text{where } a_0 = 0.217,\ a_1 = 0.259,\ a_2 = 0.338,\ a_3 = 0.186,\ tau_1 = 172.9 \text{ years},\ tau_2 = 18.51 \text{ years, and } tau_3 = 1.186 \text{ years.} \tag{9}$$

In the case of CH_4 and N_2O, the pulse decay is modeled as a simple exponential decay due to the much shorter lifetime of methane in the atmosphere:

$$CH_4\ PulseDecay = S_{CH4}(w) \times e^{-(t-w)/tau_m} \tag{10}$$

$$N_2\ OPulseDecay = S_{N20}(w) \times e^{-(t-w)/tau_n} \tag{11}$$

In all three of the above equations, w indicates the specific time step in the simulation when that particular emissions pulse occurred. The resulting pulse decays for all the prior CO_2, CH_4, and N_2O pulses are then summed together at each time step (along with the new pulses occurring at that time step) to derive the resulting emissions Seq(t), Smeq(t), and Sneq (t) (in grams of CO_2, CH_4, or N_2O) in the atmosphere at that point in time. CEAGOM then computes the resulting concentration of each of these gases at each time step from these emissions.

Once the concentrations of CO_2, CH_4, and N_2O have been obtained, the resulting radiative forcing and associated global average temperature change are computed. CEAGOM uses the following equations to compute the radiative forcing due to CO_2, CH_4, and N_2O, respectively, at each time step (see Table 8.SM.1 in [36]):

$$\Delta F_{CO2}(t) = 5.35 \ln\left(\frac{c(t)}{c_0}\right) \tag{12}$$

$$\Delta F_{CH4}(t) = 0.036(\sqrt{M(t)} - \sqrt{M_o}) - [f(M(t), N_o) - f(M_o, N_o)] \tag{13}$$

$$\Delta F_{N2O}(t) = 0.12(\sqrt{N(t)} - \sqrt{N_o}) - [f(M_o, N(t)) - f(M_o, N_o)], \text{ where} \tag{14}$$

$$f(M,N) = 0.47 \ln[1 + 2.01 \times 10^{-5}(MN)^{0.75} + 5.31 \times 10^{-15} M(MN)^{1.52}] \tag{15}$$

CEAGOM computes the change in radiative forcing and associated change in global average temperature from the preindustrial period (typically taken to be about the year 1750). Hence, the values used for c_o and M_o used in the model are the preindustrial values of 278 ppm for CO_2 and 722 ppb for CH_4 found in Table 8.2 of [37]. Furthermore, according to reference [36], the value of N_o that should be used in the radiative forcing equation for methane should be the present-day value of the N_2O concentration. Similarly, the value of M_o used in the forcing equation for N_2O should be the present day value of the methane concentration. CEAGOM addresses this by using user-supplied values for M_o and N_o that are taken to be the concentrations at the start of the simulation.

Since sulfur injection and sea spray injection both reduce radiative forcing, the resulting radiative forcing at each time step is then given by:

$$\Delta F(t) = \Delta F_{co2}(t) + \Delta F_{CH4}(t) + \Delta F_{N2O}(t) - \Delta F_{sulfur}(t) - \Delta F_{sea}(t) \tag{16}$$

The total radiative forcing reduction from sulfur injection and sea spray injection are based on a user-supplied per unit forcing reduction and the total amount of sulfur injection or sea spray deployed.

Once the change in radiative forcing is computed, the resulting change in temperature can be determined. From Chapter 6 of [38], this can be reasonably approximated by:

$$\Delta T(t) = 0.5 \Delta F(t) \tag{17}$$

The climate model in CEAGOM also recognizes that the effectiveness of each of the four geoengineering options decays with time. CEAGOM employs a simple exponential decay function for sulfur injection, iron seeding and sea spray injection that reduces the specific geoengineering's effect to 0.1% of its original value after a number of time steps equal to the lifetime have passed. If sulfur injection, iron seeding, or sea spray injection was deployed at multiple time steps, then this exponential decay is applied to each of those geoengineering injections independently and the resulting effectiveness at each time step is then determined by summing the results of these individual decays. The overall effect of any deployed geoengineering at each time step is the sum of any new increments of geoengineering added at that time step t_0 plus the residual effects of any geoengineering deployed at prior time steps.

Forests, on the other hand, can continue sequestering CO_2 for up to 70 years [39]. However, the amount of CO_2 sequestered in trees varies over time according to a more complex function than a simple exponential decay. The wood volume of a forest measured as a percentage of maximum wood volume follows a curve known as the logistic or sigmoid function [40,41]:

$$v(t) = \frac{1}{(1 + e^{-steep(t-midpoint)})}, \quad \text{where} \tag{18}$$

midpoint is the value of the logistic function's midpoint and steep is the steepness of the curve [42]. This function yields the classic "S" shaped curve. The amount of CO_2 sequestered in a forest varies with the rate of change of wood volume. Therefore, the effective sequestration over time is given by the derivative of the logistic function [43]:

$$\frac{dv(t)}{dt} = \frac{e^{-steep(t-midpoint)}}{(1 + e^{-steep(t-midpoint)})^2} \tag{19}$$

CEAGOM uses the above equation for the derivative of the logistic function to determine the amount of CO_2 sequestration over time obtained from each incremental addition of tree planting geoengineering:

$$\text{effectiveq}_{trees}(t) = q_{trees}(t_0)\frac{dv(t)}{dt} \tag{20}$$

If an increment of tree planting is deployed at a particular time step t_0, its effectiveness over time is determined by Eq. (20). Just as the case for the other geoengineering options, if incremental additions of tree planting are made by the optimization engine at prior time steps as well as the current time step, then Eq. (20) is applied to each increment independently and the results are summed to obtain the total effect of all tree planting at the current time step. The logistic function parameters steep and midpoint are user defined in CEAGOM.

A final unique feature of the CEAGOM climate model is that it computes CO_2 equivalent emissions not only for the GHG's, but for all the geoengineering options, as well. This is a very important aspect of the model since annual and cumulative emissions can be used as the primary climate constraint. As shown in the IPCC literature, these limits are specified in terms of CO_2-eq. The CH_4 and N_2O emissions are easily converted to a CO_2 equivalent value by simply multiplying them by their respective global warming potentials (GWP). Similarly, the CO_2 equivalent emissions reductions represented by the radiative forcing reduction of sulfur injection are also given by multiplying the amount of sulfur injected by the global warming potential of SO_2, the gas that is proposed for use in sulfur injection geoengineering. The GWP for SO_2 is a negative number, thereby indicating that injection of this gas into the atmosphere results in a cooling effect [44].

No such global warming potential value could be found in the literature for the sea spray geoengineering. As a result, a sea spray equivalent emissions factor was developed as part of this research. This value was determined as follows:

Salter et al. in the original paper on sea spray geoengineering estimated a radiative forcing reduction of 3.7 W/m^2 for a 45 cu. meter/s sea spray injection [45]. Using Eq. (12) with a preindustrial CO_2 concentration of 278 ppm, 3.7 W/m^2 forcing would correspond to an equivalent CO_2 concentration of 555 ppm CO_2e. From Shine et. al., 1 g of CO_2 in the atmosphere is the equivalent concentration of 1.278×10^{-16} ppm [46]. Thus,

$$Ess = 555 \text{ ppm} \times \left(\frac{1 \text{ gram } CO_2}{1.278 \times 10^{-16} \text{ ppm}}\right) \times \left(\frac{1}{45 \text{ m}^3/\text{sec}}\right)$$
$$= 9.65 \times 10^{16} \text{ grams } CO_2\text{−eq/m}^3\text{/second of sea spray.} \quad (21)$$

The equivalent negative emissions due to sea spray geoengineering then become:

$$S_{sea}(t) = Ess \times q_{sea}(t) \quad (22)$$

The total equivalent emissions are then:

$$S_{total}(t) = S_{CO2}(t) + Sm_{CO2}(t) + Sn_{CO2}(t) + S_{sulfur}(t) + S_{sea}(t) \quad (23)$$

2.4. Economics model

The CEAGOM economics model is based on well-established engineering economics principles [47]. The cost of every unit of an energy resource or geoengineering option deployed at each time step is composed of three main components. The first is a per unit variable cost, C_j, which represents the cost of producing energy from the increment of resource j or providing reduced radiative forcing from geoengineering option j. The second component is a per unit capital cost, K_j, which will be incurred if additional amounts of the energy resource or geoengineering option need to be deployed. Finally, the model also allows the user to assign a "penalty" cost, p_j, to any energy or geoengineering resource. The penalty cost enables the user to account for indirect or intangible costs which the deployment of a resource might impose, including any adverse impacts. For instance, a user could impose a penalty cost on nuclear power in order to account for the potential adverse costs of a nuclear accident or weapons proliferation.

CEAGOM also incorporates the per unit decommissioning cost, Zj, for nuclear, hydro, and coal resources. Only nuclear, hydro, and coal are assumed to have decommissioning costs that are high enough to warrant inclusion in the model.

CEAGOM also includes the ability to model a carbon tax. When a user specifies a carbon tax, CEAGOM imposes the tax on any deployment of oil, coal, or natural gas resources used to meet energy demand. CEAGOM applies the tax to both direct CO_2 emissions and to CH_4 emissions from these resources. CH_4 emissions are converted to CO_2-eq emissions by multiplying them by the Global Warming Potential for CH_4 (see Reference [44]). The total carbon tax incurred by each resource at each time step is then given by:

$$CarbonTax_j(t) = q_j(t) \times (s_j + (s_{j-m} \times GWPm)) \times CarbonTaxRate \quad (24)$$

In Eq. (24), the CO_2 emissions and CH_4 emission (converted to CO_2-eq) for each resource are determined by multiplying the quantity of the particular resource deployed by its per unit CO_2 and CH_4 emissions. These emissions for that resource at that time step are then multiplied by the user specified carbon tax rate to determine the carbon tax imposed on the resource.

The total capital, variable, penalty, and decommissioning costs for each energy resource and geoengineering option are then computed by the optimization engine based on the amount of each resource deployed in the policy. CEAGOM treats the variable and penalty costs as annual costs. The per unit capital and decommissioning costs for each resource are converted to annual capital recovery values prior to being sent to the optimization engine using the standard capital recovery factor (CRF) and sinking fund factor (SFF) equations described in Reference [47]:

$$CRF_j = \left[\frac{i}{(1+i)^{\Lambda j}-1} + i\right] \quad (25)$$

$$SFF_j = \left[\frac{i}{(1+i)^{\Lambda j}-1}\right] \quad (26)$$

CEAGOM assumes that the capital and decommissioning costs are recovered over the lifetime, Λ_j, of the resource. The capital recovery factor is applied to the capital cost since that cost is incurred when the resource is first deployed while the sinking fund factor is applied to any decommissioning cost since that cost is incurred at the end of the resource's lifetime. The resource lifetimes and discount rate used in the above equations are user-supplied.

The cost of energy efficiency is handled differently compared to all the other resources modeled in CEAGOM. Energy efficiency covers a wide range of activities from home weatherization to the installation of more efficient motors in cars and industrial processes, each of which has their own unique cost. Krewitt et al. in Ref. [33], however, developed a unique approach to this energy efficiency cost problem. They assigned energy efficiency a cost that was a fraction of Gross Domestic Product (GDP). This is the approach implemented in CEAGOM. Instead of an explicit cost per unit of energy efficiency deployed, the user provides CEAGOM with a parameter which represents the fraction of GDP per EJ of energy efficiency. CEAGOM allows the user to specify this as either a single value to be used for the entire simulation or a specific value for each time step in the simulation. The user also supplies CEAGOM with an assumed GDP value. This would typically be the forecast GDP from the first year of the simulation. CEAGOM multiplies this GDP value by the user-supplied fraction of GDP per EJ parameter. The result is then treated as a capital cost which is then annualized just like all the other resource capital costs. A single GDP value is used because it is assumed that efficiency costs will stay relatively static or even decline over time. Energy efficiency is assumed to have no variable costs.

In order to perform the optimization, CEAGOM specifies the total cost of each energy option and geoengineering option in terms of annual costs. The final annual cost for each energy resource and geoengineering option deployed at each time step is then the sum of the variable cost, the annualized capital cost, the penalty cost, the annualized decommissioning cost, and any carbon tax:

$$AnnCost_j(t) = C_j + (K_j \times CRF_j) + p_j + (Z_j \times SFF_j) + CarbonTax_j(t) \quad (27)$$

The sum of these annual costs across all the resources and geoengineering options then becomes the objective function to be minimized by the optimization engine to determine the optimal portfolio of resources to deploy at each time step.

Once the optimal portfolio of energy resources and geoengineering has been determined by the optimization engine, the total cost of the portfolio for that time step is computed by accounting for all variable, capital, penalty, carbon tax, and decommissioning costs incurred. This total cost at each time step is then brought back as a net present value by multiplying the total cost by the standard net present value factor (NPV) shown in Eq. (28) (see Ref. [47]). The NPV factor uses the same user-supplied discount rate as used in the CRF and SFF equations above. In Eq. (28), the variable t is the specific time step.

$$NPV = \frac{1}{(1+i)^t} \quad (28)$$

The net present value of each of these total annual costs is then summed together to compute a total net present value cost of the policy over the study period. The model also provides the undiscounted nominal costs for each year of the simulation and in total.

In order to reduce model complexity, CEAGOM makes several important simplifying assumptions. First, the model assumes that there is no differential inflation. The model assumes no increase in a resource's cost as it is depleted. CEAGOM also does not include any price-demand curves that would model consumer behavior. The model does, however, incorporate user-defined rates at which the use of a particular resource can be increased or decreased. These rates place limits on much each resource can be increased or decreased at each time step and are intended to represent such things as potential physical limits on how much of a given resource can be constructed in a year, or political or

regulatory barriers that might impede how quickly a resource can be phased out. Furthermore, CEAGOM includes specialized logic that decreases the maximum amount a finite resource (coal, oil, natural gas) can be deployed after a specified amount of the resource is used up. This approach provides a smooth reduction in resource usage as it is depleted. Another approach would have been to use some sort of exponentially rising cost curve; however, since the optimization is based on costs, this could have resulted in abrupt drops in resource usage that would not be realistic.

2.5. Optimization engine

The optimization engine used by CEAGOM is the fmincon constrained nonlinear optimization subroutine that is part of the MATLAB R2010a Student Version Optimization Toolbox developed by The Mathworks, Inc [48]. CEAGOM's optimization calculations occur entirely within the MATLAB fmincon subroutine. The fmincon subroutine requires the programmer to choose the algorithm fmincon will use to perform the optimization calculation from among several options included with the software. The optimization algorithm chosen for CEAGOM was the interior point method. The interior point method was chosen because it can be applied to problems where both the problem's objective function and constraint functions are nonlinear. Furthermore, it has been applied to a number of optimization problems in the electric power industry that are similar to the type of problem CEAGOM is intended to address [49].

As noted above, the objective function used in CEAGOM is the sum of the annual costs of all the energy resources and geoengineering options at each time step. Each time step is optimized independently. In addition to this objective function, the CEAGOM code also passes a series of constraint equations to the fmincon subroutine. These constraints include equations to insure that the amount of each resource deployed does not exceed the available quantity of the resource and that any change in the amount deployed is within the above mentioned rate limits. The other key constraints are the climate constraint (temperature rise, emissions, or greenhouse gas concentration limit) and the requirement to meet the energy demand, including any reserve requirements. In addition to meeting the total energy demand, CEAGOM also specifies constraint equations to insure that the specific demands for liquid energy, electricity, and direct combustion energy are met.

CEAGOM keeps track of how much of each energy resource and geoengineering option was deployed at prior time steps, as well as emissions and GHG concentration, since this is critical for the constraints in subsequent time steps. Once the fmincon subroutine returns the optimized portfolio of energy resources and geoengineering for the given time step, the CEAGOM code updates these key parameters. The total GHG emissions and resulting GHG concentration and global average temperature rise are computed based on the resource portfolio at that time step using equations 9 through 17 and 20 through 23. This includes updating the impact of any previous geoengineering deployment through the exponential decay (Eqs. (9)–(11)). In the case of tree planting, this includes updating the derivative of the logistic function (Eq. (19)) at the new time step and then multiplying that value by the amount of tree planting deployed (Eq. (20)) as described in Section 2.3. The total amount of each resource used is also updated. All these updated values are then made available for the next time step's optimization.

2.6. Data considerations

As is the case with all models, data is a key consideration. As previously noted, nearly all of the parameters in CEAGOM are user-specified. This is approximately 320 engineering, climate, and cost parameters. While not an excessive number for an IAM, several of these parameters are particularly important for CEAGOM to run properly and to provide reasonable results. These include the variable and capital costs of the resources, the resource efficiencies and energy conversion factors, the resource lifetime, the assumed discount rate, the amount of each resource available for deployment, and the per unit GHG emissions (or mitigation in the case of the geoengineering options). Several parameters, on the other hand, of less importance and can be set to zero if good data for them is not available. These include the resource decommissioning and penalty costs.

The energy demand forecast for the time period under consideration is a critical input to the CEAGOM model. This includes not only the overall energy demand, but also the demand for the transportation fuel, electricity, and combustion energy subcategories described in Section 2.2. In addition, it is important that the energy demands be specified in terms of final energy since the energy conversion equation (Eq. (1)) converts all the resource deployments into final energy values.

3. Model comparison

In order to confirm that CEAGOM could produce realistic results, it was tested against another known and accepted analysis. The data chosen for comparison was the Energy Information Administration's (EIA) Annual Energy Outlook 2015 (AEO2015) [50]. The AEO2015 provides projections of U.S. energy uses, prices, and energy-related CO_2 emissions annually for the period 2012 to 2040. In order to perform the comparison, the energy demand and price data from the AEO2015 were input into CEAGOM. The CEAGOM optimization was run and its output was compared to the resource and CO_2 emissions projections in the AEO2015. For purposes of the comparison, 2012 was used as time $t = 0$. Therefore, the simulation covered the 28 year period from 2013 through 2040. The initial values for the resources were based on the 2012 AEO2015 values. No geoengineering was allowed to deploy in the CEAGOM model since the AEO2015 did not assume any kind of geoengineering.

The projections in the AEO2015 are produced using the EIA's National Energy Modeling System (NEMS) [51]. NEMS uses a market-based approach to develop its projections. This includes accounting for regulations, standards, and market competition. NEMS models the U.S. at the regional level in order to account for regional market differences in energy supply and demand. The model balances supply and demand until the delivered prices of energy and the quantities demanded have converged to within a tolerance for each year being forecast. Macroeconomic drivers, such as GDP, employment forecasts, and disposable income, are used as inputs. NEMS directly accounts for state renewable portfolio standards and tax credits for renewables. EIA assumes that all power plant retirements that have reported on Form EIA-860 over the next 10 years will occur and explicitly models these retirements [52]. NEMS derives a set of energy demand and supply curves subject to the constraints previously noted. NEMS then iteratively determines the prices and quantities of all fuels so that the supply and demand curves in all energy markets reach equilibrium. Thus, the NEMS model used to derive the AEO2015 forecasts follows a process that is similar to an optimization algorithm. This allowed the AEO2015 to be used as a comparison to CEAGOM which is a straight-forward optimization based on resource cost subject to the various user-defined climate, ramp rate, production, and resource availability constraints.

The CEAGOM simulation using the AEO2015 energy demand and cost data yielded results that matched the AEO2015 energy resource forecasts quite well. Fig. 1 shows the comparison between the CEAGOM resource results and the AEO2015. It shows the percent difference between the CEAGOM results for the resource amounts and emissions compared to the projections in the AEO2015 for each year of the simulation. The key point illustrated by this figure lies in the magnitudes and signs of the differences between the CEAGOM and AEO2015 results. The vast majority of the results show a difference of 10% or less between the two models over the entire 28 year simulation period. Furthermore, the sign of the percent differences is also of importance. A positive percent difference indicates that CEAGOM deployed more of

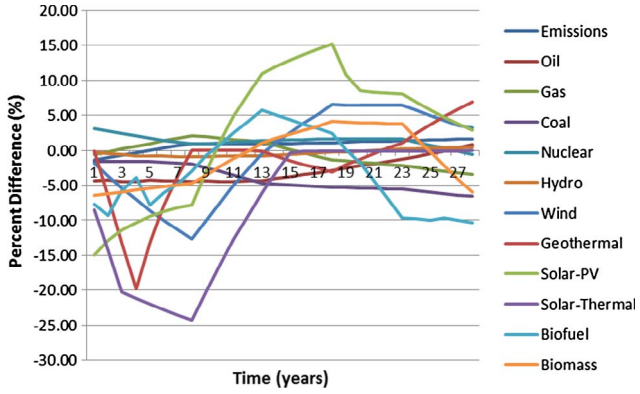

Fig. 1. CEAGOM vs EIA AEO2015 percent differences.

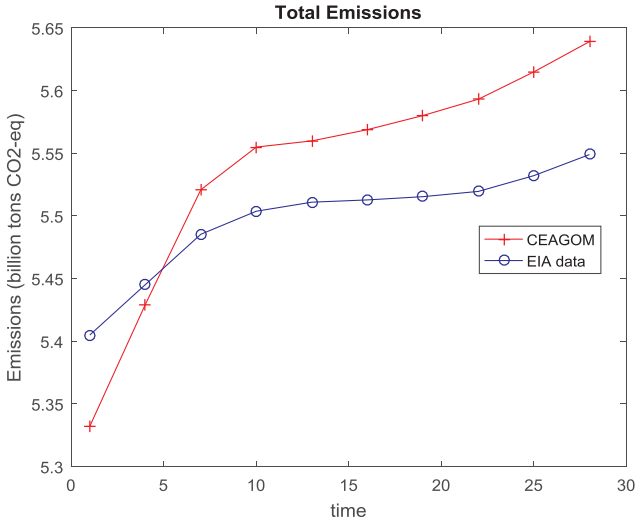

Fig. 2. CEAGOM vs EIA AEO2015 emissions results.

that particular resource in that year than the corresponding AEAO2015 projection while a negative difference represents the opposite. As shown in Fig. 1, there are similar numbers of positive and negative differences across the simulation. Therefore, the CEAGOM model was not giving consistently higher or lower results than the AEO2015. Finally, there are no obvious correlations in either the signs or magnitudes of the differences. Hence, there did not appear to be any systemic bias or error in the results. The data used to generate Fig. 1 is provided in the Supplementary Materials.

The percent differences for several of the resources were very small. The largest percent differences for hydro, nuclear, gas, oil, coal, and biomass were less than 1%, 3%, 4%, 5%, 7%, and 7%, respectively. Biofuel, geothermal, solar-PV, solar-thermal, and wind also showed generally good results, but did have percent differences in certain years of just under 11%, 20%, 16%, 25%, and13%, respectively.

One possible reason for these discrepancies in the case of coal, oil, and gas is that in the real world there is a wide range of efficiencies in the power plants, factories, and vehicles that use these fuels. Many are still relatively old and, thus, have lower efficiencies. Furthermore, the U.S. has a high proportion of truck and SUV's in its vehicle fleet that consume more fuel than standard passenger cars. CEAGOM, on the other hand, uses a single efficiency value for each of the various resources (such as oil for transportation and coal for electricity production). This would explain why CEAGOM's estimates, especially for coal and oil, were consistently lower than the AEO2015 estimate. In addition, the heat content of fossil fuels, especially coal, varies depending on where the fuel was produced. Again, CEAGOM uses a single energy content value for each resource while the AEO2015 may be using multiple heat content assumptions for its coal projections.

The reasons for the larger discrepancy between the CEAGOM results and the AEO2015 projects in some years for biofuel, solar-PV, and wind were less clear. Part of this could have been due to regulatory requirements that are explicitly modeled by the EIA in the AEO2015, but which are not included in CEAGOM. Another possibility is that since the amounts of these resources are relatively small compared to the other energy resources in the U.S., a small difference in the amount of energy met by each of these resources in the optimization calculation compared to what was assumed by the AEO2015 could result in a relatively large percentage change and corresponding difference in the resource amount. The trend of the CEAGOM results for each of these resources was still quite consistent with the AEO2015 projections and the larger discrepancies were only at certain time points. Most of the other percent differences for these resources were still under 10%. Hence, even the biofuel, solar-PV, and wind results can be considered to be quite reasonable overall between the two models.

The emissions results between CEAGOM and the AEO2015 projects were also quite close. Some calibration in the assumed per unit emissions for coal, oil, and natural gas had to be done in CEAGOM in order for those values to line up with what was apparently assumed in the AEO2015. In addition, EIA's projections are strictly CO_2 emissions at the point of consumption. They do not account for any life cycle emissions. The CEAGOM model, on the other hand, includes life cycle emissions for energy resources such as hydro and nuclear, and also includes efficiency values that take into account the full "well-to-wheels" energy use of the process. Calibrating the per unit emissions for coal, oil, and natural gas and removing the life cycle emissions in the CEAGOM analysis yielded CO_2 emissions that differed by only 0.05 to 0.08Gt from the AEO2015 projections (a difference of less than 2%). This is illustrated in Fig. 2.

4. Discussion

As the above model comparison results show, CEAGOM is able to provide resource and emissions projections that are very comparable to those obtained from the highly detailed analyses in the AEO2015. The AEO2015 forecasts are based on sophisticated statistical and econometric analyses. By contrast, CEAGOM is purely an optimization engine. Therefore, the fact that CEAGOM was able to match the AEO2015 resource and emissions forecasts as well as it did using the AEO2015's cost and energy demands as inputs is significant. As discussed in detail in Section 3, the vast majority of the CEAGOM results showed less than a 10% difference with the AEO2015 projections. Even in the cases with somewhat higher percent differences, CEAGOM still matched the overall shape and trend of the AEO2015 forecasts. In policy analysis, having a good grasp of the basic trend of a variable can be as important as the absolute value of the variable.

In addition to the cost and energy demand data, the model comparison effort showed that the assumed rates at which resources could be added or decreased, as well as the assumed available amount of each resource, were very important to the outcome. These parameters had a significant influence on how well the CEAGOM results matched the AEO2015 forecasts. This was a good indicator of which parameters are especially important to calibrate when performing an analysis with CEAGOM.

A significant benefit of CEAGOM is the speed at which it runs. The 28 year simulations run for the model comparison with the AEO2015 ran in about 30 s actual clock time on an Intel i3 laptop computer. This compares very well with similar scenarios run employing the widely used TIMES model with reported run times between 80 and 440 min (computer type unspecified by the authors) [53].

In addition to the validation study presented here, the authors have successfully used the CEAGOM model in two research studies. These studies showed that CEAGOM can successfully perform analyses at both

a global and a regional scale. One study examined the optimal mix of energy resources that should be deployed globally over the course of the entire 21st century to keep the world within a 2 °C average temperature rise and the role geoengineering could play in this [54]. The second study examined the optimal mix of energy resources that the US and China should each pursue in order to meet the emissions targets laid out in the 2014 agreement between President Barak Obama and President Xi Jinping [55].

As with all models, CEAGOM has limitations. One limitation is that the model optimizes each time step independently. By performing the optimization on each time step individually, it is possible to have a scenario where highly emitting resources are used right up until the climate limit is reached, then potentially very costly geoengineering has to be deployed to counteract the emissions and hold to the climate constraint. A more optimal policy might have been to reduce the use of the high greenhouse gas emitting resources earlier and replace them with other resources rather than having to employ the geoengineering. However, CEAGOM's approach is in line with similar analysis tools. For example, the advanced TIMES model uses a linear programming optimizer and EIA's NEMS model also solves forward one year at a time [27,56].

Another limitation of CEAGOM is that the model does not recognize the potential spatial aspects of the energy optimization problem. For example, there is a tremendous amount of solar energy potential in North Africa, but it is not feasible to transmit this electrical energy to loads in East Asia. Hence, the model could call for the deployment of resources that cannot get to where the demand is located.

A third issue is that CEAGOM does not include any means of modeling consumer behavior in response to price changes nor does the model adjust prices as resources are depleted. This is potentially important in determining energy usage and cost as various resources are used up. CEAGOM partially addresses this issue by ramping down the allowed usage of certain non-renewable resources once they reach a specified amount of depletion. However, this does not fully address the price-demand relationships that exist in the real world. Furthermore, CEAGOM does not model any feedbacks between climate change and the economy. As a result, changes in energy demands or prices that could result from changes in climate are not captured by the model.

Finally, CEAGOM is a deterministic model, not a stochastic model. Hence, it does not directly address the issue of uncertainty in its input parameters and the impact this uncertainty could have on its results.

5. Conclusions

CEAGOM offers considerable benefit and valuable insights to a wide range of users, including researchers, decision-makers, and students. CEAGOM was built from scratch and is designed so that it is easy to understand and use while still incorporating all the interacting elements of energy resource characteristics, climate impact, and cost. As with all models, CEAGOM has its limitations. However, CEAGOM still provides results that are comparable to those obtained through far more involved analyses.

Since nearly all of the parameters used in the model are user defined, CEAGOM offers tremendous flexibility. The parameters can be modified in a matter of minutes and the model itself runs very quickly, thereby allowing multiple "what-if" scenarios to be made in a very short period of time. A user could literally run dozens of CEAGOM simulations in the time it would take to set up and run a single simulation on one of the more complex IAM tools. This allows policy-makers and analysts to assess a range of potential strategies to determine if they can meet specified energy and climate constraints and at what cost. In addition, this ability to run multiple cases in a short period of time makes CEAGOM an excellent screening tool which can be used to develop scenarios that can then be analyzed with more complex IAM tools. Furthermore, CEAGOM's explicit inclusion of various geoengineering options as potential elements in the solution expands the range of strategies that can be explored. Finally, CEAGOM is written in the widely used MATLAB programming language which allows it to be readily employed by a range of users in industry, government, and academia, especially those users who may not have a deep background in modeling. These features make CEAGOM a very useful tool to both policy-makers and researchers as they grapple with the difficult decisions regarding energy and climate change that lie ahead. Its ease of use, accessibility, and speed also make it a potentially valuable teaching tool in an academic environment.

A full description of the CEAGOM model, including source code and user guide, is publicly available through the Portland State University Library (see reference [55]).

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Appendix A. Nomenclature

a_0, a_1, a_2, a_3	the coefficients of the CO_2 emissions pulse equation
$AnnCost_j(t)$	annual cost of resource j ($ trillion) – computed value
c(t)	atmospheric concentration of CO_2 (ppm)
c_o	preindustrial CO_2 concentration (ppm)
C_j	per unit variable cost of energy or geoengineering resource j ($ trillion/unit of resource j/year)
CarbonTaxj(t)	carbon tax incurred by resource j at time t ($ trillion) – computed value
CarbonTaxRate	carbon tax per ton of CO_2-eq emissions ($/metric ton) – user supplied
CRFj	capital recovery factor for resource j – computed value.
Ess	equivalent emissions of sea spray (grams CO_2-eq/(cu meter/s))
f(t)	forecast final energy demand (EJ)
GWPm	global warming potential of methane – user supplied
i	discount rate (%) – user supplied
j	index of energy resource and geoengineering options
k_j	energy conversion factor (EJ per unit of resource j)
K_j	per unit capital cost of energy or geoengineering resource j ($ trillion/unit of resource j) – user supplied
L_j	amount of resource j available or resource j potential
M(t)	atmospheric concentration of methane (ppb)
M_o	preindustrial concentration of methane (ppb)

N(t)	atmospheric concentration of N_2O (ppb)
N_o	present-day N_2O concentration at the start of the simulation (ppb)
p_j	per unit penalty cost of energy or geoengineering resource j ($ trillion/unit of resource j/year) – user supplied
$q_j(t)$	units of resource j deployed
$Q_j(t)$	total amount of energy provided by resource j (EJ)
s_j	emissions of CO_2 per unit of energy resource used
(grams CO_2 emitted/unit j)	user supplied
$s_{j\text{-}m}$	emissions of CH_4 per unit of energy resource used
(grams CH_4 emitted/unit j) –	user supplied
$S_x(t)$	total emissions of GHG x (either CO_2, CH_4, or N_2O) (grams)
Seq(t)	equivalent CO_2 emissions at time t after accounting for decays of all prior
CO_2	emissions pulses (grams)
Smeq(t)	equivalent CH_4 emissions at time t after accounting for decays of all prior
CH_4	emissions pulses (grams)
Sneq(t)	equivalent N_2O emissions at time t after accounting for decays of all prior
N_2O	emissions pulses (grams)
$S_{sulfuer}(t)$	sulfur injection converted to CO_2 equivalent (CO_2-eq)
$S_{sea}(t)$	sea spray injection converted to CO_2 equivalent (CO_2-eq) – computed value
$S_{total}(t)$	total emissions converted to CO_2 equivalent (CO_2-eq)
SFFj	sinking fund factor for resource j – computed value
t	time (years)
tau_1, tau_2, tau_3	atmospheric lifetimes of CO_2
tau_m	atmospheric lifetime of CH_4
tau_n	atmospheric lifetime of N_2O
v(t)	logistic function
Z_j	per unit decommissioning cost of resource j ($ trillion/unit of resource j) – user supplied
$\Delta F(t)$	total change in radiative forcing (W/m^2)
$\Delta F_{CH4}(t)$	change in radiative forcing due to methane (W/m^2)
$\Delta F_{CO2}(t)$	change in radiative forcing due to CO_2 (W/m^2)
ΔF_{N2O} (t)	change in radiative forcing due to N_2O (W/m^2)
$\Delta F_{sea}(t)$	change in radiative forcing due to sea spray injection (W/m^2)
$\Delta F_{sulfur}(t)$	change in radiative forcing due to sulfur injection (W/m^2)
$\Delta T(t)$	change in global average temperature from preindustrial levels (°C)
η_j	energy conversion efficiency or capacity factor of resource j (%)
Λj	lifetime of resource j – user supplied

Appendix B. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apenergy.2018.02.145.

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